Design of impulse UWB volumetric antenna integrating dielectric material

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***Abstract*— In this paper, a guidelines for designing a volumetric ultra-wideband (UWB) antenna is proposed. The methodology is applied for the design of various travelling waves antenna shapes. A comparative study between various design geometries leads to a particularly interesting antenna dimensions: The K antenna. We demonstrate the use of an appropriate dielectric material is an efficient way to reduce the antenna dimensions. Furthermore, the behavior of an antenna filled with resin intended for Ground Penetrating Radar is validated using the experimental results.**

Keywords— Ultra Wide Band antennas; Ground Penetrating Radar

I. INTRODUCTION

The demand for increasingly wider bandwidths for applications such as radar, imaging and telecommunications requires an appropriate antenna design. The limitation of the antenna dimensions is critically for radar applications, especially at low frequencies. For example, a radar system installed on Tunnel Boring Machine (TBM) must provide identification of large obstacles which can obstruct during digging (e.g. other tunnels, cavities, boulders, foundations, archaeological remains, etc.,) as well as soil changes (e.g. from gravel to fractured rock) (NETTUN Project) [1]. This radar system must radiate at low frequencies in order to achieve better penetration in the soil, ideally few decades of Megahertz.

The use of an appropriate dielectric material is an efficient way of reducing the antenna dimensions. One can expect that the antenna size can be decreased almost by a factor of square root of relative permittivity of the used material. However, the nature of the dielectric material significantly modifies the behavior of the antenna and therefore a rigorous analysis of the radiation structure is necessary.

The paper is organized as follows: Section II explains the UWB antenna design requirements and the guidelines proposed for the design of volumetric antenna. The various antenna designs and its output response are discussed. In section III, we describe the impact of dielectric material on reducing the antenna size. Section IV demonstrates the design of K antenna and discusses the obtained results. Section V summarizes the future scope of this work and section VI concludes the paper.

II. DESIGN METHODOLOGY

A. Impulse UWB antenna requirements

For impulse UWB applications, the antenna design has to satisfy the following conditions:

- Matched (S_{11} parameter lower than -10dB) over a very large bandwidth (at least one decade, which is equivalent to 164%).
- Less dispersive in order to radiate short signal which is advantageous for the radar imaging processing.

In general, Ultra-Wide Band (UWB) travelling wave antennas follow the above mentioned criteria. In addition, volumetric antennas enable higher gain. The directivity aimed by the antenna depends on the type of application. For communications, many UWB antennas have been designed to have omnidirectional radiation patterns but for radar applications, higher directivity is required.

B. Volumetric Antenna Design Guidelines

a) Balanced antenna

UWB antenna can be considered as a succession of transmission line sections in which transverse dimensions W and h depend on characteristic impedance and dielectric permittivity of the substrate [2]. The design methodology proposed here is to gradually modify the transverse dimensions to ensure that the wave is radiated during the propagation. In order to avoid reflection and large dimensions, the characteristic impedance evolves for example from 50Ω to 250Ω, while designing the balanced antenna (Fig. 2.), then W/h ratio must satisfy the following equations:

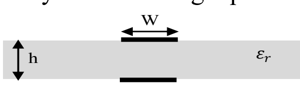


Fig. 1. Transverse dimensions of balanced line

$$\frac{W}{h} = \begin{cases} \dfrac{4e^{A}}{e^{2A}-2} & for\ \dfrac{W}{h} < 2 \\[2ex] \dfrac{1}{\pi}\left[\begin{array}{l} B-1-\ln(2B-1) \\ +\dfrac{\varepsilon_r - 1}{2\varepsilon_r}\left\{\ln(B-1)+0.39-\dfrac{0.61}{\varepsilon_r}\right\} \end{array}\right] & for\ \dfrac{W}{h} > 2 \end{cases} \quad (1)$$

Where:

$$A = \frac{Z_0}{120}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}(0.23 + \frac{0.11}{\varepsilon_r}) \quad (2)$$

$$B = \frac{377\pi}{Z_0\sqrt{\varepsilon_r}} \quad (3)$$

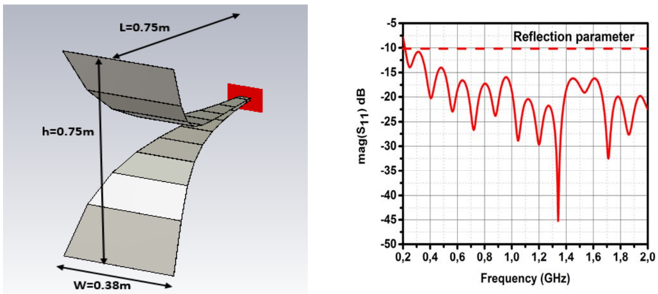


Fig. 2. Balanced Antenna and reflection coefficient magnitude

A systematical study has been performed on a symmetric antenna using the radiation in the air for the frequency band of 200 MHz to 2 GHz, by varying the section line length and characteristic impedance. The selected input line allows the antenna to operate in the desired high frequency range. The length and the aperture of the antenna are limited by the half of the highest wavelength of the spectrum.

The antenna shape and its reflection parameter are given in Fig.2.

b) Unbalanced antenna

The feed of the balanced antenna requires the introduction of a balun, which limits its bandwidth. In order to change from balanced to unbalanced structure, a ground plane is introduced and the antenna's input follows the geometry of microstrip line. The equations (1)-(3) are used again by replacing Z_0 by $Z_0/2$ and h by $h/2$.

An example of unbalanced antenna and its reflection parameter is shown in Fig. 3

To obtain the K antenna as shown in Fig. 4, the structure of unbalanced antenna is modified by adding vertical plate at the back of the antenna and horizontal plates.

The dimensions of K antenna [3] for the desired frequency band of [0.2; 2GHz], can be calculated in terms of the highest wavelength (λ_{max}) radiated in the frequency band ($L=\lambda_{max}/3.75$, $h=\lambda_{max}/5$, $W=\lambda_{max}/10$). The low frequency behavior of the antenna has been enhanced with the integration of a magnetic loop.

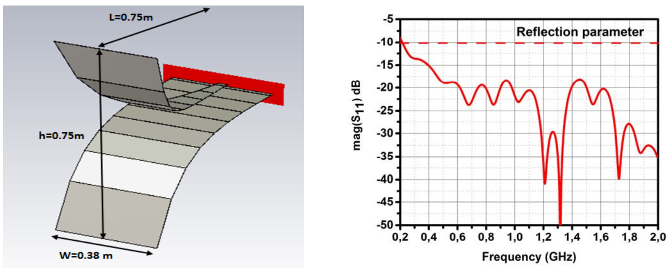


Fig. 3. Unbalanced Antenna and reflection coefficient magnitude Balanced

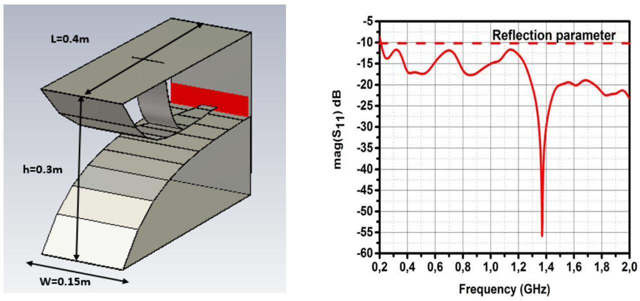


Fig. 4. K Antenna and reflection coefficient magnitude

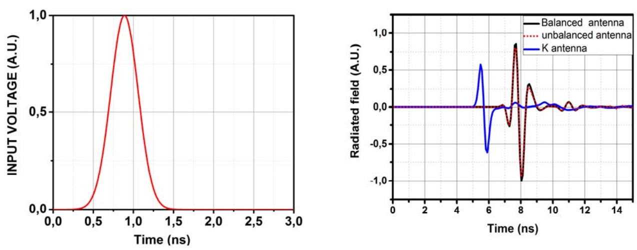
Indeed, the dimension of the loop's length has been chosen in order to ensure a good (-10 dB) reflection coefficient for lower frequency band limit [4]. Thanks its lowest size, K antenna (Fig. 4.) is often chosen for pulse UWB applications [5].

c) Behavior of the presented antennas in term of dispersion

Radiated far fields by the three designed antennas (balanced, unbalanced and K) have been assessed to compare their transient behaviors. Amplitudes are normalized to the maximum radiated field (Fig. 5). Balanced and unbalanced antennas radiate an electric field of similar shape and amplitude. K antenna ensures low dispersion of the transient waveform. However the field has lower magnitude because the size of antenna is smaller compared to the others antennas.

III. Method To Reduce The Antenna Size By Filling It With A Dielectric Material

The solution to reduce the size of the antenna is to fill it with a dielectric material. The main antenna dimensions are divided by square root of the dielectric permittivity. Table I illustrates an example of a K antenna designed for the frequency band of 200 MHz to 2 GHz. The relative permittivity of the dielectric is equal to 6. For the simulations with CST Microwave Studio, the dielectric is considered without losses. It is obvious from the table, the antenna filled with dielectric material shows the reduced dimensions compared to the one in the air medium.



(a) (b)

Fig. 5. Dispersion analysis: (a) Input voltage (b) Radiated field of the antennas

TABLE I. ILLUSTARTIONS OF REDUCUING ANTENNA DIMENSIONS

K antenna in the air	K antenna with dielectric (ε_r=6)
L=0.4m H=0.3m W=0.15m	L=0.16m H=0.12m W=0.06m

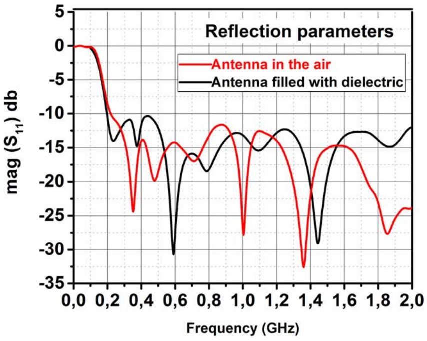


Fig. 6. Reflection coefficient magnitude

Fig. 6. shows the reflection parameters of the antennas filled with air (red) and the dielectric material (black). A good adaptation (S11<-10 dB) is obtained for both of the antennas over the frequency band [0.2;2 GHz].

IV. Example Of An Antenna Realization And Tests In Complex Environmentment

The antenna for GPR application aims to radiate low frequency pulses in order to penetrate the ground as deeper as possible (given the dimensional constraints), even if this induces losing performance in terms of resolution and blind zone extension.

The selected filling material is a polyurethane dielectric resin from Axson Technologies (reference RE11880/RE1020).

We have measured the relative permittivity of resin using the Dielectric Assessment Kit by Schmid & Partner Engineering AG. The Dielectric Assessment Kit (DAK) is ideal for all applications where high-precision dielectric parameter measurements (permittivity, conductivity, loss tangent) are required, including applications in electronic, chemical, food, and medical industries.

Fig. 7 shows the measured real and imaginary parts of the dielectric permittivity of a resin sample.

From those characteristics, a dielectric model was extracted in order to be used in a rigorous electromagnetic simulation (CST Microwave Studio). The insertion of the designed K antenna into a metallic cavity leads to a KHORN antenna. The metallic cavity was filled using this resin. The optimization of the antenna shape was realized by taking into account the dielectric parameters of the material and the presence of the metallic walls of the cavity.

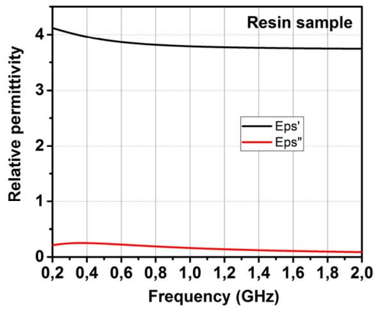


Fig. 7. Real part (Eps') and Imaginary part (Eps'') of relative permittivity - resin sample

To remove resonances between the lower strip of the K antenna and the cavity, the strip was widened to keep in contact with the vertical walls of the cavity.

The designed KHORN antenna has been manufactured (Fig. 8.) and test measurements have been performed on this structure when the antenna is in contact with the soil. The adaptation bandwidth strongly depends on the nature of the soil and its humidity. To illustrate this dependence, measurements of reflection coefficients have been performed in the same location at two different times. The obtained results are depicted in Fig. 9.

a)

b)

Fig. 8. KHORN Antenna: a) Metallic structure, b) Antenna, filled using the resin, in contact with soil

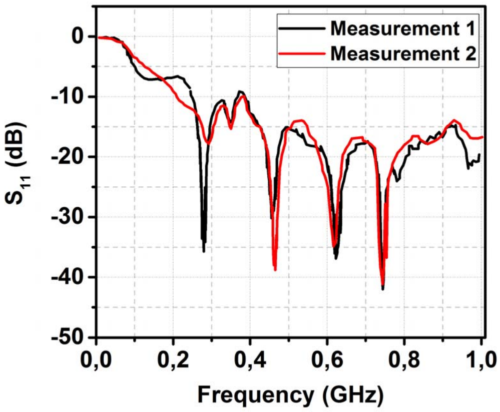


Fig. 9. Measured adaptation parameter; influence of soil humidity

Unfortunately, the soil was very wet during the first experimentation (measurement 1). This explains the reason for higher reflection coefficient in case of measurement 1 at low frequency content, whereas the measurement 2 demonstrates the good adaptation starting from 205 MHz.

V. Future Works

For GPR applications and for reducing the antenna dimensions, it is important to use dielectric materials with high dielectric permittivity from which we are able to extract an accurate model

We propose to develop a new dielectric material based on different test mixtures in collaboration with a materials specialist [6] – [9].

The motivation of such research is to significantly improve the material properties, especially in term of electromagnetic characteristics.

According to the chosen metal, the oxidation problems in the metallic structure of antenna / material interface will be considered.

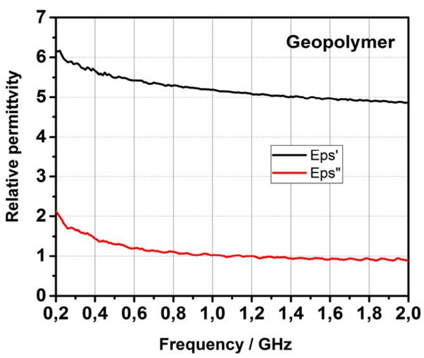


Fig. 10. Real part (Eps') and Imaginary part (Eps'') of relative permittivity - Geopolymer

The outcome of these researches would constitute a great improvement in particular for the design of optimized antennas.

These studies were already initiated and the dielectric characteristics for Geopolymer material are shown in Fig. 10.

The behavior of antennas integrating this material and other ones under development will be analyzed next months.

VI. Conclusion

Various geometries of UWB antennas have been designed to work in the frequency band of [200MHz; 2 GHz]. For GPR application, a particular shape of antenna, integrated into a metallic cavity which has been filled with resin was designed and manufactured. To further enhance the compactness of the antenna, the development of dielectric materials with high dielectric permittivity is mandatory.

Research on geopolymer has been initiated and the first samples are realized and tested. Next step will be the design of antennas integrating this material.

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